

Appendix A

Assessment of Northern Pike Habitat in California's Central Valley and Potential Impact of Introduction

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by

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ABSTRACT

The northern pike (*Esox lucius*) is a non-native predatory fish species that was illegally introduced into Frenchman Reservoir and Lake Davis in California's northern Sierra Nevada. Pike introductions in other regions have demonstrated that they have the potential to become the dominant fish species, preying upon and out-competing other fishes. To prevent pike from moving down the Middle Fork Feather River and reaching the Central Valley, they were eradicated from Frenchman Reservoir in 1991-1992. Lake Davis was chemically treated in 1997. Pike were rediscovered there in 1999, although the exact reason for their return is not known. Examination of pike biology, environmental requirements, and introduction history indicates that they have the potential to survive in many areas of the Central Valley and become abundant in at least some habitats. Nearly every native fish species would be vulnerable to pike predation. This is of particular concern because many of these native species are already in decline. Results of introductions of pike elsewhere, and of other predatory fish in California, suggest that pike could have a devastating effect on existing Central Valley fish communities. The overall ecosystem effect of the resultant change in species composition is impossible to predict, but given the current stressed state of the Central Valley and San Francisco Bay Estuary aquatic environments, any additional negative impacts should be avoided. Therefore, the only prudent management alternative is to use all means necessary to prevent northern pike from reaching the Central Valley.

KEYWORDS

Northern pike, *Esox lucius*, Central Valley, native fishes, impact, habitat

INTRODUCTION

The northern pike (*Esox lucius*) is a non-native predatory fish species that was illegally introduced into Frenchman Reservoir, on Little Last Chance Creek, and Lake Davis, on Big Grizzly Creek, in California's northern Sierra Nevada. Both creeks are tributary to the Middle Fork Feather River, which drains into the Sacramento-San Joaquin River system of the Central Valley. Both reservoirs are above 1,500 m (5,000 ft) elevation; they are cool, shallow, and have abundant submerged aquatic vegetation, conditions which are similar to those found in lakes in the pike's native range (Figure 1). Pike introductions in other regions have demonstrated that they have the potential to become the dominant fish species, preying upon and out-competing other fishes. Should pike reach the Central Valley, they potentially could irreversibly damage the aquatic ecosystem and fisheries in the San Francisco Bay-Delta estuary and its watershed, as well as harm other areas of California and the western United States.

Attempts were made to eradicate pike in both lakes where they have been found in California. The California Department of Fish and Game (CDFG) successfully eradicated pike from Frenchman Reservoir and the adjoining Sierra Valley in 1991 and 1992. In 1994, pike were discovered in Lake Davis and the reservoir was chemically treated to eradicate them in October 1997. Pike were rediscovered in the lake in May 1999, although the cause of their return has not been determined. Also, the chemical treatment of Lake Davis was highly controversial in the local community because it temporarily eliminated the lake's rainbow trout (*Onchorhynchus mykiss*) fishery, which attracted many tourists, and because the town of Portola depended on the lake for part of its water supply.

Because of local opposition to further chemical treatment of the lake, the CDFG worked with other government agencies and the local community to devise a strategy to control the pike population, to contain the pike within Lake Davis, and to remove as many pike as possible from the reservoir without chemical treatment. Control and

removal measures included public education, law enforcement, electrofishing, trapping, and experimental use of underwater detonation cord.

Since February 2000, although about 55,000 pike have been removed from the lake, pike numbers have continued to increase and have negatively impacted the trout fishery. Recognizing that the threat of pike to the Lake Davis trout fishery was not diminishing and that the potential for its spread to the Central Valley was increasing with the burgeoning pike population, CDFG, in cooperation with local, State, and Federal agencies, as well as the local community, has proposed another eradication project to eliminate the threat posed by pike, while addressing the protection of public and environmental health and considering economic concerns.

This report will summarize pike biology and environmental requirements and describe consequences of other pike introductions. It will examine the potential for the diverse habitats in the Central Valley drainage, including the upper Sacramento-San Joaquin Delta (delta) and Suisun Marsh, to support pike populations and assess the probable impact of pike on biological resources, especially native fishes. It will not evaluate the impact of northern pike invasion of the canal and reservoir system of the Federal Central Valley Project and the State Water Project. This is a likely occurrence if pike become established in the delta, from which water for those water projects is drawn.

NORTHERN PIKE BIOLOGY

Northern pike is one of the most widely distributed freshwater fish in the northern hemisphere; it is native to lakes and rivers between 41 and 65° latitude in Europe, Asia, and approximately 54% of the total area of fresh water in North America (Carlander et al. 1978). It has been introduced into almost all states in the United States (Figure 1) (Crossman 1978). Legal introductions have taken place to control nuisance or overabundant fish populations, to enhance sport fisheries, or both.

Pike is classified as a cool-water fish, although it can tolerate a wide range of environmental conditions. Ideal habitat consists of beds of aquatic macrophytes growing in shallow, clear water less than 12 m (39 ft) deep in mesotrophic to eutrophic environments. All life stages use vegetation, but it is especially important for the egg and

juvenile stages. Pike prefer areas that are sheltered from wind and without much current (Bry 1996).

Northern pike have a well-deserved reputation as top carnivores, with a torpedo-like body shape, flattened head, and razor-sharp teeth. The caudal fin is large and the dorsal and anal fins are placed far back on the body, close to the caudal fin. This allows a pike to launch itself from ambush at high speeds to capture fast-swimming prey (Moyle and Cech 1982).

Northern pike spawn from February to March at the southern limit of their geographic distribution and during May and June farther north (Billard 1996). Increases in water temperature and light intensity stimulate spawning (Fabricius and Gustafson 1958).

Pike become sexually mature at 1 to 3 years old (Diana 1983) and at lengths of 18 cm (7 in) for males to 26 cm (10 in) for females (Grimm and Klinge 1996). Pike may mature earliest when large adults are absent (Diana 1983). Egg production ranges from 6,000-250,000 eggs per female, depending on size (Weitkamp 2003).

Pike spawn in both rivers and lakes. Ideal spawning areas in rivers are backwater areas with submerged vegetation, low-gradient pools, marshy areas connected to rivers, meadows or floodplains inundated with floodwater, or gradually sloping banks (Bry 1996). In lakes, pike spawn in littoral zones that have aquatic vegetation, marsh areas, tributaries to the lake, and ditches adjacent to the shoreline (Bry 1996). Pike may migrate up to 78 km (48 miles) to spawning areas, but most spawning migrations are <15 km (9 mi) (Carbine and Applegate 1948). Currents $>1.5 \text{ m sec}^{-1}$ (5 ft sec^{-1}) can block spawning migrations and at all times pike prefer areas with water velocities $<5 \text{ cm sec}^{-1}$ (2 in sec^{-1}) and an overall gradient of $<0.5\%$ (Inskip 1982).

Spawning depths are typically shallow. Ideal spawning depth is $<1 \text{ m}$ (3 ft) (Inskip 1982), but in deep lakes some spawning occurs as deep as 7 m (23 ft) at the end of the spawning season when water temperatures in shallower areas are too high (Bry 1996).

Submerged vegetation is critical for spawning; without it, reproductive success is low (Hassler 1970) because pike scatter their eggs over large areas of vegetation to which the eggs adhere (Bry 1996). Ideal spawning habitat has vegetation coverage $>80\%$ that is

dense up to 15 cm (6 in) above the substrate and is loosely compacted so that water circulates around the eggs. Spawning substrate can include compacted vegetation, branches of woody plants and fallen leaves. Vegetation that does not occupy much of the water column and covers only 60% of the substrate is less desirable. Least ideal is thinly scattered vegetation or debris (Inskip 1982).

Adults return to spawning areas when water temperatures are in the range of 1-4°C (34-39°F); preferred spawning temperature is 7-18°C (44-64°F) (Hassler 1970) (Table 1). Duration of incubation ranges from 5 days at 20°C (68°F) to 30 days at 6°C (43°F) (Billard 1996).

After hatching, the yolk sac larvae use adhesive glands on their heads to adhere to vegetation in a vertical position. The yolk sac is absorbed in 5-16 days at 10-19°C (50-66°F). From 9-14 days after hatching the adhesive glands gradually decrease in size and the larvae detach from the vegetation and swim to the surface to fill their air bladders (Weitkamp 2003). They then hold a horizontal position in the vegetation. Larvae are 8.5-9 mm (0.30-0.35 in) at hatching and 12-15 mm (0.5-0.6 in) at swim up (Billard 1996). Thereafter, larvae grow approximately 10 mm (0.40 in) week⁻¹ (Raaf 1988).

Vegetation is critical for survival in that it provides cover and food. The vegetation can be alive or decaying, aquatic or terrestrial; it may be emergent, submergent, or floating (Casselman 1996). Grasses and sedges are preferred, but other types of vegetation are used as well (Casselman and Lewis 1996).

Mortality is high during incubation and early fry rearing (Weitkamp 2003). Mortality from spawning to hatch is commonly about 80%. Rapid temperature changes, high turbidity, and high insoluble iron (65 ppm) appear to substantially reduce embryo and larva survival (Weitkamp 2003).

After they reach about 20 mm (0.80 in), pike move from the spawning area to more sparsely vegetated areas (Franklin and Smith 1963; Masse et al. 1991). This movement may be stimulated by a decrease of water level (Masse et al. 1991), elevated water temperature (Masse et al. 1988), increased light intensity (Hunt and Carbine 1950), and increased feeding competition (Forney 1968; Gravel and Dube 1980). They can become cannibalistic as small as 21 mm (0.82 in) (Hunt and Carbine 1951), but

cannibalism rates are low when they can emigrate (Franklin and Smith 1963; Derksen and Gillies 1985).

Young-of-the-year northern pike, measuring about 65 mm (2.5 in), need a combination of submerged and emergent vegetation with an optimum density of 20-50% (Anderson 1993). Casselman and Lewis (1996) found that young-of-the-year pike preferred shallow water, generally about 10 cm (4 in) in depth for every 12 mm (0.50 in) of body length.

Adult pike rely mostly on submergent vegetation (Casselman and Lewis 1996). They require a minimum aquatic vegetation cover of 30% (Grimm and Backz 1990). Adults are usually found in water <4 m (13 ft) in depth, but sometimes live in water up to 12 m (39 ft) deep (Casselman 1996). They commonly inhabit the macrophyte-open water interface within 300 m (980 ft) of shore (Chapman and Mackay 1984; Weitkamp 2003). This transitional area is important because it provides cover for ambushing prey (Inskip 1982; Chapman and Mackay 1984). As ambush predators, northern pike tend to remain inactive about 80% of the time and are most active at dawn and dusk (Weitkamp 2003). Pike generally remain within small home ranges, except for movements to spawning areas (Weitkamp 2003).

Adult female northern pike grow more quickly than males; they are commonly 7.7% larger than males and have a linear growth potential that is 40% greater than males (Casselman 1996). Mean fork lengths for both sexes from 82 areas in North America, Europe, and Asia ranged from 18 cm (7 in) at age 1 to 69 cm (27 in) at age 12 (Table 2) (Raaf 1988; Casselman 1983). The minimum size at age 1 was 9 cm (3.5 in) and the maximum size at age 12 was 97 cm (38 in).

As with most fishes, northern pike diet varies with life stage. Initially, larval pike feed on zooplankton, but switch to aquatic insects as they grow larger (Hunt and Carbine 1950). Young-of-the-year pike feed on invertebrates in the vegetation (Bry 1996). Once they reach about 25 cm (10 in), they start feeding on fish such as minnows or bluegills (*Lepomis macrochirus*) (Savino and Stein 1989). At this point, they become “opportunistic piscivores that prey upon more abundant and vulnerable species. They have the ability to switch from one food source to another” (Mann 1982). Soft-rayed fish are preferred prey, as they provide pike with the highest energy and growth (Beyerle and

Williams 1968). However, they may still prey on invertebrates if fish are not readily available (Chapman et al. 1989), become cannibalistic (Kipling 1983), or even feed on frogs and ducklings (Lawler 1965; Frost 1954; Allen 1939; Hunt and Carbine 1950; Lux and Smith 1960; Lagler 1956).

NORTHERN PIKE ENVIRONMENTAL REQUIREMENTS

In addition to the need for aquatic vegetation at all life stages as described above, water quality is an important factor for northern pike reproduction, survival, and growth. The most important water quality parameters are temperature, dissolved oxygen, pH, salinity, total dissolved solids, and turbidity.

Temperature

Northern pike tolerate a wide range of temperatures (Table 1). Optimal temperature for egg incubation is 7-18°C (44-64°F) (Hokanson et al. 1973). Optimum temperature for larvae (22-23°C [72-73°F]) (Casselman and Lewis 1996) is considerably higher than for eggs or juveniles (19°C [66°F]) (Casselman and Lewis 1996). Adults grow and survive best at temperatures <19°C (66°F) (Casselman and Lewis 1996). Thus, optimal temperature, especially for growth, decreases with age. Lower and upper lethal temperatures range from <3°C (38°F) for larvae (Hokanson et al. 1973) to 29-30°C (84-86°F) for adults. Temperatures below freezing are likely lethal to any life stage (Casselman and Lewis 1996).

Spawning temperatures also vary greatly. Whereas spawning generally occurs at temperatures of 7-18°C (44-64°F) (Hassler 1970), it has been observed at water temperatures as low as 4°C (39°F) (Sukhanova 1979) and as high as 18°C (65°F) (Fabricius and Gustafson 1958). When incubation temperature ranges from 7-18°C (44-64°F), 80% of the eggs hatch (Hokanson, et al 1973), but if embryos experience a sudden water temperature drop or a prolonged low water temperature of 5°C (41°F), mortality increases to 100% (Hassler 1970).

Dissolved oxygen

As with temperature, northern pike can tolerate a wide range of dissolved oxygen (DO) conditions (Table 1). Generally, adult pike require DO levels $>1.5 \text{ mg l}^{-1}$, although they have been observed at a DO level of 0.04 mg l^{-1} in near-freezing water. At higher temperatures, the lethal DO concentration is $0.5\text{-}1.5 \text{ mg l}^{-1}$ (Casselman 1978). Feeding ceases when dissolved oxygen is $<2 \text{ mg l}^{-1}$ (Casselman and Lewis 1996). Optimal food consumption, food conversion efficiency, and growth rate are highest when dissolved oxygen is 100% of saturation, which can be as high as $12\text{-}13 \text{ mg l}^{-1}$. Any decrease in DO below saturation significantly reduces growth (Adelman and Smith 1977).

pH

The pH in northern pike lakes usually ranges from 6.1 to 8.6 (Margenau et al. 1998), although some populations of northern pike are found at pH as low as 5.0 (Inskip 1982; Harvey 1980).

Pike sensitivity to pH differs depending on life history stage. Embryos and fry are more sensitive to pH than other life stages; a pH <5 causes mortality in fry (Inskip 1982). Fingerling and larger northern pike can survive when the pH as high as 9.0-9.5 (McCarraher 1962). Reproduction may be impaired when the pH <5 and >9.0 (Inskip 1982). Growth is typically most rapid in slightly alkaline waters (pH 7-8).

Salinity and Total Dissolved Solids

Northern pike are basically freshwater fish, but in their native range in Europe are often found at low salinities in estuaries. In the shallow coastal waters of the Baltic Sea, they have been found in salinities of 12-15 ppt (Schlumpberger 1966), which is close to their lethal limit of 18 ppt (Jenkins and Burkhead 1994). In the Baltic Sea, they reproduce at salinities of up to 7 ppt (Svardson, pers. comm., cited in Toner and Lawler 1969).

In high salinity areas, pike migrate to fresh water to spawn (Johnson and Muller 1978). In the northern Bothnian Sea, pike migrated from brackish water to a coastal stream to spawn, where they remained for up to 2 months before returning to the estuary (Muller 1986).

These high salinity tolerances are inconsistent with the range of total dissolved solids (TDS) deemed suitable for pike in a habitat suitability index model (Inskip 1982). This model assumes that productivity in northern pike lakes, and suitability for pike, increases as TDS increases from 0 to 0.08 ppt. From 0.08 to 0.8 ppt, suitability is high and constant. At greater TDS levels, habitat suitability for pike decreases until it reaches zero at 3.5 ppt (Inskip 1982).

Siltation and Turbidity

Northern pike embryos are sensitive to high turbidity when it is due to inorganic material, such as silt. A siltation rate of 1 mm day⁻¹ was associated with embryonic mortality of $\geq 97\%$ in two Missouri River reservoirs (Hassler 1970). In an experiment by Durand and Gas (1976; cited in Billard 1996), survival to 8 days post-hatch was reduced by 43% and 97% below a hatchery control at suspended solids content of 0.5 mg l⁻¹ and 30 mg l⁻¹, respectively.

Turbidity also affects adult northern pike growth. In Dauphin Lake, Manitoba, Craig and Babluk (1989) found that high turbidity (low water transparency) negatively affected growth because pike are visual predators and high turbidity restricts their ability to see prey. With every increase in transparency of 1 m (3 ft) over the 1-3-m (3-10-ft) range, pike weight increased 6%.

EFFECTS OF NORTHERN PIKE INTRODUCTIONS

Historically, some salmonids and northern pike have existed in equilibrium in North America where specific habitat and geomorphologic conditions created a predominant lack of species overlap based on habitat and water temperature requirements (J. Casselman, Ontario Ministry of Natural Resources [OMNR], pers. comm.).

However, there are not many areas in North America where northern pike and rainbow trout or anadromous salmonids are historic native residents in the same water bodies (T. Margenau, Wisconsin Department of Natural Resources [WDNR], pers. comm.; R. Pierce, Minnesota Department of Natural Resources, pers. comm.). Rainbow trout tend to be associated with coastal waterways more than with inland water systems in this hemisphere. Most of the areas where historic cohabitation between native

populations of rainbow trout and northern pike has persisted over time are in Alaska (J. Casselman, OMNR, pers. comm.; D. Rutz, Alaska Department of Fish and Game [ADFG], pers. comm.; C. Skaugstad, ADFG, pers. comm.). Much of the historic range of pike in the continental United States, in states such as Wisconsin and Minnesota, has native populations of brook trout (*Salvelinus fontinalis*) and lake trout (*Salvelinus namaycush*) as historic cohabitants (T. Margenau, WDNR, pers. comm.). In the more northerly latitudes of North American northern pike range, such as Canada and Alaska, pike have resided in equilibrium with native salmonid species that include lake trout, brook trout, arctic char (*Salvelinus alpinus*), arctic grayling (*Thymallus arcticus*), mountain whitefish (*Prosopium williamsoni*), inconnu (*Stenodus leucichthus*), dolly varden (*Salvelinus malma*), and bull trout (*Salvelinus confluentus*) (J. Casselman, OMNR, pers. comm.; D. Rutz, ADFG, pers. comm.).

Alaska

Northern pike are native north of the Alaska Range and in some areas in western Alaska. In these waters, chub and minnow species, as well as lake trout, arctic char, and grayling commonly co-occur with pike (D. Rutz, ADFG, pers. comm.). In western Alaska, some very large lakes contain stable self-sustaining populations of northern pike and rainbow trout (D. Rutz, ADFG, pers. comm.). Lakes where northern pike and salmonid species have persisted in equilibrium typically have similar habitat characteristics; generally they are deep, cold, clear, and well oxygenated. In these lakes the littoral zone (<3 m [10 ft] deep) makes up $\leq 5\%$ the total habitat and thick aquatic vegetation is almost absent, so that pike have marginal spawning habitat and little opportunity to prey on salmonids (D. Rutz, ADFG, pers. comm.). Also, northern pike grow slowly and have a lower metabolic rate in cold water, so they are less active, need less food, and are more unlikely to expend unnecessary amounts of energy in the pursuit of prey. This decreases predation mortality rates of northern pike on other fish species (C. Skaugstad, ADFG, pers. comm.).

Lake trout is the salmonid species that most commonly co-exists with pike in Alaskan lakes. Lake trout are large enough that pike are unable to prey on them during times when adult lake trout move into the shallows to spawn.

Except where they have a deep water refuge in lakes or a clear, cold, fast-flowing refuge in streams, rainbow trout do not persist in the presence of pike. This is probably due to the fact that rainbow trout tend to occupy the same habitat as northern pike if these refuges do not exist (D. Rutz, ADFG, pers. comm.).

Northern pike were illegally introduced into south-central Alaska in the early 1950s. A series of 100-year flood events over the next 30 years resulted in pike spreading throughout the Susitna River drainage. Pike are most numerous in those parts of the Susitna River drainage that consist of shallow lakes and sloughs and slow clear tributary streams. Pike are less numerous or absent from those parts of the Susitna River drainage that are turbid, fast moving, or that have extremely cold water (Fay 2002). In many of the lakes and streams of this area that were historically dominated by salmon, trout, and char, only pike remain (B. Stratton, ADFG, pers. comm.).

The typical course of events after northern pike introduction into a south-central Alaska lake was as follows: “Introduced pike initially grow rapidly because of the large food base; they reproduce successfully and the abundant offspring also reproduce; the lake soon contains thousands of small pike; the pike eat everything in the lake, including each other; after a period of 5 to 10 years the lake contains nothing but 25-50-cm (10-20-in) pike” (Fay 2002).

Numerous examples of this sequence have been reported. Northern pike consumed essentially all trout, salmon, and char after being illegally introduced into the Soldotna Creek drainage (a tributary to Kenai River) in the 1970s and many Anchorage area lakes in the late 1980s (B. Stratton, ADFG, pers. comm.). The main prey base in these waters now consists of leeches and insect larvae (Associated Press 2003).

An exception to this general course of events has been reported for 1,000-hectare (2,500-acre) Harding Lake, about 72 km (45 mi) southeast of Fairbanks (C. Skaugstad, ADFG, pers. comm.). This lake has a maximum depth of 43 m (140 ft) and a littoral zone that covers about 33% of the surface area. After the introduction of northern pike, least ciscos (*Coregonus sardinella*), burbot (*Lota lota*), lake trout, and arctic char persisted in the lake. All these species are pelagic or reside in deep water. However, telemetry studies reveal that pike >50 cm (20 in) move to pelagic areas in search of prey, so exposure of pelagic species to pike predation is reduced but not eliminated. This may

explain why the cisco population has increased as the pike population has declined recently due to water levels below the point where most aquatic vegetation is accessible. Subcatchable rainbow trout were stocked in this lake until about 13 years ago, when it was discontinued because pike predation on the trout resulted in low angler catch rates.

Rainbow trout have been eliminated by pike predation in many small lakes (30-40 hectares [75–100 acres]) in south-central Alaska. Three-spine stickleback (*Gasterosteus aculeatus*), which also occupied these same lakes, were then eliminated by pike predation after the trout were gone. Three-spine sticklebacks are not normally preyed upon by pike, but became the only fish species available once the trout had been eliminated. As in the Soldotna Creek drainage and the lakes near Anchorage, the diet of the northern pike in these lakes now consists primarily of invertebrates, such as leeches, fresh-water clams, and dragonfly larvae. Northern pike in these lakes are stunted. Most fish are similar sized, with the largest fish being, on average, 55-60 cm (21-24 in) (T. McKinley, ADFG, pers. comm.).

Canada

Water temperature strongly influences northern pike distribution and population dynamics in Canada and, thus, their co-occurrence and interactions with other fishes (J. Casselman, OMNR, pers. comm.). Pike are most numerous in southern Canada where waters tend to be warmer and more mesotrophic. In the summer, pike use warm, shallow bays where grasses, sedges, and other aquatic vegetation are found. This habitat selectivity has allowed lake and brook trout to co-exist with pike and, in far northern Canada where pike are less abundant, for arctic char and grayling to occupy the same waters as pike.

Rainbow trout have been introduced to interior Canada to support recreational fisheries or to prey on smaller-bodied invasive fish species. Rainbow trout (called “steelhead”) and pike are both present in the Great Lakes, but the vastness of these lakes and the minimal habitat overlap between these two species, greatly reduces the predation impact of pike on rainbow trout.

Piscivorous fish introductions in small lakes in Quebec led to changes in species and size composition of other fish species. Lakes with piscivores, including northern

pike, largemouth (*Micropterus salmoides*) and smallmouth bass (*M. dolomieu*), and yellow perch (*Perca flauescens*), had half the number of small-bodied species of lakes without piscivores and the lakes with piscivores were dominated by long-lived, large, deep-bodied species, such as members of the sucker, perch, and sunfish families (Chapleau and Findlay 1997).

Idaho

Information on the impact of introduced northern pike is available from two lakes in the panhandle of northern Idaho (N. Horner, Idaho Department of Fish and Game, pers. comm.): Coeur d'Alene Lake and Hayden Lake.

Coeur d'Alene Lake

Coeur d'Alene Lake is a complex system, consisting of a 12,750-hectare (31,487-acre) main lake and eight lateral lakes, for a total surface area of about 14,200 hectares (35,000 acres). This second largest natural lake in Idaho has a maximum depth of 60 m (200 ft) and a mean depth of 24 m (80 ft). Approximately 10% of Coeur d'Alene Lake consists of relatively shallow, weedy bays; this habitat type also occurs in the lateral lakes.

Westslope cutthroat trout (*Oncorhynchus clarki lewisi*), bull trout, and whitefish (*Coregonus* sp.) are native to the lake, but the fish fauna has been greatly augmented by introduced species. As the result of an illegal transplant, northern pike were first discovered in one of the lateral lakes in 1974. Besides northern pike, introduced species include kokanee (*O. nerka*), land-locked Chinook salmon (*O. tshawytscha*), largemouth and smallmouth bass, black crappie (*Pomoxis nigromaculatus*), pumpkinseed (*Lepomis gibbosus*), yellow perch, tench (*Tinca tinca*), black (*Ameiurus ameius*) and brown bullhead (*A. nebulosus*), reidside shiner (*Richardsonius balteatus*), longnose dace (*Rhinichthys cataractae*), northern pikeminnow (*Ptychocheilus oregonensis*), and longnose and largescale (*Catostomus macrocheilus*) sucker.

Adult cutthroat trout (33-46 cm [13-18 in]) are vulnerable to predation by large pike during their spawning migration to and from tributary streams and juvenile fish are susceptible to pike predation when they migrate to the lake at ages 1-3. However, their

low density in the lake is believed due to a combination of factors, including pollution and habitat degradation in an important spawning tributary, competition with introduced salmonids, pike predation during cutthroat migration periods, and smallmouth bass predation along lake shorelines.

Chinook salmon and kokanee are not as vulnerable to northern pike predation as cutthroat trout because they typically convert to a pelagic life history after entering the lake. Kokanee are only a significant part of the northern pike diet in the fall when they are near the shoreline spawning.

The size of the northern pike population appears to be limited by abiotic factors, primarily weather during the spring spawning season. Water level fluctuations during the spring spawning season can dewater eggs deposited on flooded vegetation and spring storms can drop water temperatures and lower egg survival.

Density of northern pike in Coeur d'Alene Lake is low, only about 10% of the standing crop found in their native waters. Due to limited recruitment of young pike and substantial angler harvest of fish >age 2, food competition is low and growth is exceptional compared to that reported in the literature. Age 2-3 pike range from 53-71 cm (21-28 in); age 6 fish reach 9 kg (20 lb); and age 8 fish, although uncommon, are ≥ 14 kg (30 lb).

Pike in Coeur d'Alene Lake are opportunistic feeders, but tend to select fusiform, soft-rayed species such as cutthroat trout, northern pikeminnow, and suckers. Yellow perch, small crappies, sunfish, and a few young-of-the-year pike are found in pike stomachs.

Hayden Lake

Hayden Lake is a natural lake with a surface area of about 1,600 hectares (4,000 acres), maximum depth of 56 m (185 ft), and mean depth of >30 m (100 ft). Most of the shoreline is steep and rocky, but the bays are shallow and weedy. The littoral zone makes up about 10-15% of the surface area.

Fish species in Hayden Lake include rainbow trout, westslope cutthroat trout, largemouth and smallmouth bass, bullhead, black crappie, pumpkinseed, yellow perch, and tench. Northern pike became established in about 1990.

The results of trout fishery management in Hayden Lake have been unsatisfactory. Rainbow trout were first stocked in the lake in 1988 in an effort to improve the quality of the fishery, as cutthroat trout recruitment from the three tributary streams was low and their growth was slow. The lake is now annually stocked with 100,000 cutthroat trout fingerlings and 270,000 rainbow trout. Current estimates are that only 10,000 trout are being harvested annually.

Predation by northern pike in the lake is only one factor affecting the trout fishery. Others include predation by smallmouth bass, loss of fish with water spilling out of the lake during high-water periods in the spring, and reduced quality of stocked trout that are now trucked from a distant hatchery that has water chemistry much different than Hayden Lake.

Angling has been used to reduce pike abundance in the lake. However, small pike are still abundant and enough large pike remain to attract intense fishing pressure, especially during winter when pike congregate in the north arm of the lake. Anglers that ice fish for pike in the north arm saturate the surface with rods, and catch up to six pike angler⁻¹ day⁻¹ early in the season. Although most of the pike caught are 2-yr-old fish in the 53-71 cm (21-28 in) size range, an angler harvested a 17.5-kg (38 lb, 9 oz) pike in 2002 that tied the state record.

Limited stomach analysis of pike harvested during the winter ice fishery found mostly fishing bait (herring and smelt); small perch, crappie, and pumpkinseed were the most common forage fish. Trout are generally not present in this bay in the winter. Pike recruitment is limited by the same factors that affect Coeur d'Alene Lake: fluctuating lake level during the spring and late spring storms that abruptly lower water temperature. The effect on pike of the replacement of established vegetation by invasive Eurasian milfoil (*Myriophyllum spicatum*), starting in 1997-1998, is unknown.

Colorado

Northern pike have been introduced into at least eight Colorado reservoirs (Orabutt 2006). Information on the interactions between northern pike and other species has been documented for two of these reservoirs on the Middle Fork of the South Platte River in central Colorado: Eleven Mile Reservoir and Spinney Mountain Reservoir.

Eleven Mile Reservoir

Eleven Mile Reservoir is located at an elevation of 2,620 m (8,600 ft) near the city of Hartsell. Eleven Mile Reservoir covers about 1,375 hectares (3,400 acres) and has a maximum depth of 30 m (100 ft). The littoral zone takes up about 15% of the surface area (D. Krieger, Colorado Division of Wildlife [CDOW], pers. comm.).

Pike were introduced into Eleven Mile Reservoir by the State of Colorado in the late 1960s and early 1970s to control white sucker (*Catostomus commersonnii*), longnose sucker (*Catostomus catostomus*), and common carp (*Cyprinus carpio*), three species that were having a negative effect on fingerling trout production. A trophy trout fishery was maintained by annually stocking 500,000-1,000,000 100-150-mm (4-6-in) rainbow trout. This stocking level was sufficient to allow enough fish to survive pike predation to reach adult size and also to provide a prey base to create a trophy pike fishery. More recent reductions in the number of trout stocked has negatively affected the trout fishery and, also, reduced growth and body condition of pike (D. Krieger, CDOW, pers. comm.).

Increased angler effort and harvest of northern pike controlled the pike population in Eleven Mile Reservoir. A 1994 survey indicated that anglers tend to keep northern pike they catch, even those <50 cm (20 in). This may be the reason why the northern pike population in Eleven Mile Reservoir is more balanced with food resources than in some other Colorado waters (D. Krieger, CDOW, pers. comm.).

Northern pike < age 2 in Eleven Mile Reservoir feed almost exclusively on scuds. From age 2-3, they prey primarily on stocked sub-catchable trout. In 2003, seven pike in these age classes had ingested up to five 150-cm (6-in) trout within 24 hours after the reservoir was stocked with trout. The diet of pike >age 3 now consists mainly of trout ≥ 200 mm (8 in), crayfish, and young-of-the-year carp. No cannibalism by pike has been noted (J. Spohn, CDOW, pers. comm.).

Spinney Mountain Reservoir

Spinney Mountain Reservoir is located at an elevation of 2,650 m (8,700 ft) on a plain about 7.5 km (4.5 mi) upstream of Eleven Mile Reservoir and covers about 990 hectares (2,450 acres). Maximum depth is about 12 m (40 ft) and 60-70 % of its area is in

the littoral zone. Submergent aquatic vegetation is abundant in this littoral zone, but few grasses or sedges are found there (J. Spohn, CDOW, pers. comm.).

The South Platte River upstream of Eleven Mile Reservoir was chemically treated to remove all fish prior to the construction of Spinney Mountain Reservoir. This included killing northern pike that had emigrated upstream from Eleven Mile Reservoir. Some pike may have survived the chemical treatment, as northern pike were never intentionally stocked at Spinney Mountain Reservoir. A trophy trout fishery in the reservoir, which was maintained by trout stocking from 1982 to 1999, was essentially eliminated by 1999 due to pike predation. Stocking was discontinued until 2001, when the CDOW developed a fisheries management plan for the reservoir (Gerlich 2001).

Stomach analysis from 75 pike >60 cm (24 in) collected in 1999 and 2000 provides indirect evidence of how rapidly pike consumed stocked trout in the reservoir. Although a total of 566,000 8-25-cm (3-10-in) rainbow trout were stocked from 1997 to 1999, the pike examined in 1999 and 2000 contained only one rainbow trout. This may be indicative of how quickly pike consumed stocked trout. Biologists with the CDOW concluded that the northern pike population needed to be reduced in order to maintain the trophy trout fishery in the reservoir (Gerlich 2001).

The primary prey of northern pike in Spinney Mountain Reservoir initially consisted of nongame species such as suckers. Pike had effectively reduced the numbers of these forage species by 1995 and began to target trout as their main prey species afterwards. When trout stocking was discontinued after 1999, pike growth and body condition soon suffered; growth rate of pike \geq age 6 was reduced by 50-67% (Gerlich 2001).

Based partly on public input, the CDOW implemented a trophy trout management strategy at Spinney Mountain Reservoir in 2001. A decline in the number of large pike, and the likelihood that few pike would exceed 76 cm (30 in) if deprived of adequate forage, led to a change in trout stocking strategy; only trout >30 cm (12 in) would be stocked. Also, trout were stocked in the fall just prior to surface ice formation rather than in spring to take advantage of lower winter metabolic rates of pike. Pike metabolic demand and prey consumption are at their lowest level by the end of November. Combined with trout mean winter growth rate of 25 mm (1 in) month⁻¹ in this reservoir,

this meant that fewer trout could be stocked, fewer trout would be consumed by pike in the winter, and trout would be large enough in the spring to avoid predation by all but the largest pike. The success of this management plan is still being evaluated (Gerlich 2001).

Pike size-class structure in the reservoir changed after implementation of the 2001 fisheries management plan; they appear to be growing faster and the largest pike are reach lengths up to 122 cm (48 in), with a concomitant increase in body condition. This growth enhancement may be related to the 2001 draining of Antero Reservoir, which is upstream of Spinney Mountain Reservoir and may have resulted in a large influx of suckers into Spinney Mountain Reservoir (J. Spohn, CDOW, pers. comm.).

Recent stomach content analysis of pike in Spinney Mountain Reservoir is not very informative. Pike up to age 2 preyed almost exclusively on scuds. Stomachs of 2-3-year-old pike were almost always empty; those few with food contained suckers or naturally reproduced brown and rainbow trout from the river upstream. Pike >age 3 were scarce in the sample and also generally had empty stomachs (J. Spohn, CDOW, pers. comm.).

Arizona

Information on the impact of a northern pike introduction is available for 50-hectare (123-acre) Parker Canyon Reservoir, located 8 km (5 mi) north of the Mexican border in southeastern Arizona at an elevation of about 1,525 m (5,000 ft) (D. Mitchell, Arizona Game and Fish Department [AGFD], pers. comm.). The reservoir was constructed exclusively for angling recreation, has no inflow or outflow, and is maintained from rainfall run-off. It is steep-sided, deep, and does not freeze over in winter.

Northern pike were first discovered in the reservoir by an angler who caught one in 1998. This is the only reservoir in southern Arizona that is known to contain pike. The fish were probably illegally introduced from Upper Lake Mary, which is south of Flagstaff, or from Elephant Butte Reservoir, New Mexico. Both locations are at least 480 km (300 mi) from Parker Canyon Lake (D. Mitchell, AGFD, pers. comm.).

Pike do not consistently reproduce in the lake because spawning habitat is scarce and variable. Water level and submerged vegetation for spawning are dependent on

annual precipitation in the watershed. In 1999, a few 23-25-cm (9-10-in) pike were caught in gill nets. Thereafter, juveniles were captured in 2001 and 2002, but have not been collected since then.

Rainbow trout provided a good fishery year-round until the discovery of northern pike. Annually, from October through March, 20,000-25,000 25-30-cm (10-12-in) rainbow trout are stocked. Presently, the trout fishery ends in May because of low catch rate and resumes when stocking starts again in October. Almost all pike >41 cm (16 in) have rainbow trout in their stomachs until after the trout have disappeared for the summer; trout is the only prey item found in this size pike.

The population structure of the warm-water fishes in this reservoir has been altered since the discovery of pike. Before pike introduction, bluegills were abundant and many were ≥ 15 cm (6 in). In 1999, after the discovery of pike, the population was reduced and most fish were ≤ 5 cm (2 in); bluegill were found in 19% of pike stomachs. Presently, bluegills have essentially disappeared. Redear sunfish (*Lepomis microlophus*) and largemouth bass have suffered similar fates.

In contrast, the green sunfish (*Lepomis cyanellus*) population is expanding. In the past, green sunfish were infrequently caught and their population was thought to be small. Perhaps the loss of bluegill and redear sunfish has somehow enhanced habitat conditions for green sunfish. For unknown reasons, no green sunfish have been found in pike stomachs.

THREATS TO CENTRAL VALLEY NATIVE FISHES

Most rivers in the Central Valley have at least one special status native fish species, either listed as threatened or endangered or considered a species of special concern (Table 3). These, as well as other native and introduced species, might be negatively impacted if northern pike become established in the Central Valley, if their range overlaps significantly that of pike, and if pike are successful predators on at least one life stage.

Based on the northern pike's preference for soft-rayed fishes with fusiform bodies, most native fish, except for tule perch (*Hysterocarpus traski*), would be preferred prey. In contrast, many introduced fish species, such as catfish and various sunfish

species are deep bodied and/or spiny-rayed. This potential difference in vulnerability to pike predation could result in a decrease of native fishes and an increase in non-native populations. An example of how pike might affect native fish communities in the Central Valley is seen in the impact of redeye bass (*Micropterus coosae*) on native fishes in the Cosumnes River (P.B. Moyle, pers. comm.). The recently invading bass have caused hardhead (*Mylopharodon conocephalus*), Sacramento suckers (*Catostomus occidentalis*), California roach (*Lavinia symmetricus*), and Sacramento pikeminnows (*Ptychocheilus grandis*) to be eliminated from large sections of the river.

Not all native species, or all life stages of individual species, would be equally vulnerable to pike predation because of habitat selection, temporal distribution, or size. Based on these criteria, a rough order of species vulnerability can be postulated (Table 3) and is used for the organization of the prey species discussions which follow.

Sacramento splittail (*Pogonichthys macrolepidotus*) may be the most vulnerable native fish species to pike predation. Splittail migrate upstream in winter and early spring to spawn in areas of flooded vegetation, such as berms along rivers and flooded bypasses. Spawning is most frequent in March and April, when water temperatures reach 14-19°C (57-66°F) (Moyle 2002). Adults inhabit shallow water in sloughs that have emergent vegetation, primarily in Suisun Marsh and the north and west delta (Moyle 2002). Juveniles also inhabit shallow areas with abundant vegetation without strong current (Wang 1986). Northern pike will likely prey on all life stages of splittail, as their size and body shape make even adults suitable prey for large pike and, except for Suisun Marsh, habitat overlap may be extensive.

It is likely that the young life stages of salmonids would be vulnerable to pike predation. These include Chinook salmon; steelhead (anadromous rainbow trout); and, to a lesser extent, resident rainbow trout. The existence of four distinct runs of Chinook salmon (fall, late-fall, spring, and winter) means that juveniles will be rearing in the rivers year-round and migrating downstream through the delta for many months. For example, juvenile fall-run Chinook salmon rear in most Central Valley streams for 1-7 months during late winter and early spring and migrate back to the ocean in the spring when water levels are high (Moyle 2002). Juvenile spring-run Chinook salmon (currently listed as threatened) rear in the upper Sacramento River and its east-side

tributaries, where they spend 3-15 months before migrating to the ocean from January to April (Moyle 2002). Juvenile winter-run Chinook salmon (listed as endangered) rear for 5-10 months in the upper Sacramento River and migrate downstream from September to January. Late-fall-run juveniles rear for 7-13 months in the upper Sacramento River and migrate to the ocean from April to October.

To the extent to which juvenile Chinook salmon congregate near shore and in shallow water, they will be vulnerable to pike predation. This behavior mostly occurs when they are rearing in the rivers and, at times, in the delta, so the success of pike in colonizing the upstream river systems and the delta will also determine the impact of pike predation on Chinook salmon. Structures such as diversion dams, bridge pilings, and pump platforms that make juvenile salmon vulnerable to other predators may also serve as ambush points for pike. While migrating downstream, salmon smolts tend to be near the surface and in midstream, so their vulnerability to pike predation at that time likely will be dependent on prevalence of these structures.

Central Valley steelhead (listed as threatened) occur mainly in the Sacramento River system; the principal remaining wild populations spawn in Deer and Mill creeks and in the lower Yuba River (Moyle 2002). Young remain in their natal rivers for 1-2 years before migrating to the ocean. Like Chinook salmon, they will be most vulnerable to pike predation if pike are successful in colonizing the upstream rivers and as they migrate past instream structures that provide pike with ambush points.

Resident rainbow trout (indistinguishable from steelhead, except for life history characteristics) would probably be less vulnerable to pike predation than steelhead because they do not migrate downstream; thus, they would only be exposed to pike predation if pike colonized the upriver areas they inhabit.

Sacramento suckers occur throughout the Central Valley watershed and their fusiform shape would make them ideal prey for northern pike. Juveniles seek out shallow, weedy, nearshore areas as a refuge from predators (Moyle 2002), but that behavior also would favor predation by pike. In those areas of the Central Valley that pike colonize, they would likely be significant predators of Sacramento suckers up to at least age 4 (ca. 20 cm [8 in]).

The Sacramento pikeminnow, a predator itself, would likely be a preferred prey item of northern pike in the Central Valley. Pikeminnows are widespread in the Central Valley, including the delta (Moyle 2002). Juveniles tend to stay in shallow water, whereas larger fish inhabit deeper areas. Northern pike possibly would be a competitor, as well as a predator, of Sacramento pikeminnows.

Special weight must be given to delta smelt (*Hypomesus mercedis*) when considering the ecological consequences of northern pike invasion of the Central Valley. Delta smelt are currently listed as threatened, but, along with other pelagic species in the delta, are in severe decline. Adults generally live in the top 3 m (11 ft) of the water column in mid-channel. They are approximately 50-75 mm (2-3 in) long and have a 1-year life cycle and low fecundity (Moyle et al. 1992). They migrate upstream and inshore to spawn in shallow water from February to May at water temperatures of 7-15°C (45-59°F) (Wang 1986). Eggs adhere to rocks, gravel, tree roots, and emergent vegetation (Moyle 1976; Wang 1986). Their spawning period may overlap that of pike. At that time they would be most vulnerable to pike predation; adults could be consumed by adult pike and newly hatched larvae could be eaten by larval pike. Once delta smelt move offshore, they would inhabit an area seldom occupied by pike.

Longfin smelt (*Spirinchus thaleichthys*) (a species of special concern) is euryhaline and anadromous; juveniles and adults are in both fresh and salt water. They move upstream in late summer and fall into the lower and middle delta, Sacramento River, and adjacent sloughs prior to spawning the following February-April. Eggs are deposited on rocks or aquatic plants (Moyle et al. 1995). As for delta smelt, adult and larval longfin smelt would be most vulnerable to pike predation at that time.

Another native minnow, the hardhead, (a species of concern) is present in low to mid-elevation streams in the Central Valley (Moyle et al. 1995). They prefer clear, deep pools with sand-gravel-boulder substrates and slow water velocity (Moyle and Nichols 1973; Knight 1985; Moyle and Baltz 1985). Adults remain in the lower half of the water column (Knight 1985) and juveniles concentrate in shallow water close to stream edges (Moyle and Baltz 1985). If northern pike colonize the stream reaches inhabited by hardheads, juvenile residing in shallow water could be subject to pike predation.

Other native minnows have the physical characteristics and, at least for some life stages, habitat preferences that might make them susceptible to pike predation. These include Sacramento blackfish (*Orthodon microlepidotus*), hitch (*Lavinia exilicauda*), speckled dace (*Rhinichthys osculus*), and California roach.

Tule perch habitat selection could make them highly susceptible to pike predation because they are typically associated with submerged vegetation and complex riparian cover in rivers, the delta, and Suisun marsh (Moyle 2002). In the presence of prey with the fusiform shape preferred by pike, their deep body shape may reduce predation on them by pike. However, if preferred prey is scarce, tule perch would likely be as vulnerable to pike predation as bluegill and redear sunfish.

River (*Lampetra ayresi*) (a species of concern) and Pacific (*L. tridentata*) lampreys are other native species that are potential prey of invading northern pike. Elsewhere lampreys were found to be about 1% of the diet of age 2-3 pike (Mann 1982). River lampreys are most abundant in the lower Sacramento-San Joaquin River system, including tributaries such as the Stanislaus and Tuolumne rivers (Moyle 2002). Pacific lampreys are found in many streams in the Central Valley. Both species spawn in fresh water and the larvae (ammocoetes) bury themselves in mud and/or sand and spend about 4 to 7 years filter feeding before metamorphosing and migrating to the ocean (Moyle 1976). Although present for such a long period, the ammocoetes would be unavailable to pike until they emerged from the substrate. Adult river lampreys are small enough (25-31 cm [10-12 in]) (Moyle 2002) that they also might be preyed upon by pike when they migrate back to fresh water in the fall.

THREATS TO NON-NATIVE FISHES

Many introduced fish species might also be impacted by northern pike invasion, either through predation or competition. The most likely prey among introduced species are juvenile common carp and goldfish because they inhabit aquatic vegetation and nearshore areas and have been preferred prey of pike elsewhere. Other non-native species likely to be affected by pike are American shad (*Alosa sapidissima*) during rearing in upstream areas, threadfin shad (*Dorosoma petenense*) when spawning inshore in spring, inland silversides (*Menidia beryllina*) in their preferred nearshore habitat, and

yellowfin (*Acanthogobius flavimanus*) and shimofuri (*Tidentiger bifasciatus*) gobies in the shallow areas they typically inhabit. Pike are likely to compete with other introduced predators, such as striped bass (*Morone saxatilis*) and the four species of centrarchid basses that inhabit the Central Valley.

PREDICTED INVASION SUCCESS OF NORTHERN PIKE IN CENTRAL VALLEY WATERWAYS

This section describes the habitat conditions in Central Valley waters (Figure 2) that would be accessible to invading northern pike and evaluates the probability of successful colonization by pike. Particular emphasis is given to water velocity, aquatic vegetation, and water level stability during spawning and incubation periods; water quality parameters related to suitability for pike are also included. Many areas of the Central Valley are likely to be habitable by pike, but the best habitat should have low water velocity, abundant submerged vegetation, low turbidity, stable water levels in late winter and early spring, and favorable year-round temperatures. As pike move extensively to find suitable spawning and feeding habitat, all these conditions do not have to be located in one place.

These variables, and others, are included in a Habitat Suitability Index (HSI) model for northern pike that was developed by Inskip (1982) as a tool for impact assessment and habitat management. The model is based on hypothetical relationships between pike and habitat, and not on proven cause and effect relationships; it has not been tested against field population data. It is used here to focus attention on factors most likely to be useful for predicting northern pike invasion success. The model consists of nine variables:

V_1 – Ratio of spawning habitat <1 m (3 ft) deep (when water temperature is suitable for spawning) to summer habitat area. Spawning begins when temperature reaches 8°C (46°F) and ends when temperature remains $\geq 13^\circ\text{C}$ (55°F) for several days.

V_2 – Decrease in water level during embryo and fry stages. These stages combined last about 52 days, with the first 24 days being especially critical. Pike prefer to spawn in water <1 m (3.3 ft) deep, but may spawn up to 7 m (23 ft) deep (Bry 1996).

A decrease in water level that exposes eggs or fry during the critical period would cause 100% mortality.

V₃ – Percent of summer habitat area with emergent or submergent aquatic vegetation or submerged terrestrial plants. Habitat is most suitable in the range of 25-75%.

V₄ – Total dissolved solids in summer. Suitability increases from 0 to 0.080 ppt, is constant from 0.08 to 0.8 ppt, and decreases to 0 from 0.8 to 3.5 ppt. This is inconsistent with pike salinity tolerance in the Baltic Sea, where they inhabit areas up to 15 ppt salinity (Schlumpberger 1966).

V₅ – pH is suitable from 6.0 to 9.0.

V₆ – Average length of the frost-free season. This postulates that normal gonadal development may be impaired if the cold-weather season is too short. This is based on inference from yellow perch, as no data are available for pike.

V₇ – Maximum weekly average surface water temperature. Whereas 19-20°C (66-68°F) is best, any maximum weekly temperature below 25°C (77°F) is suitable.

V₈ – Percent pools and backwaters with water velocity <5 cm sec⁻¹ (2 in sec⁻¹) in summer. This is only applicable to riverine habitat. This is a straight-line relationship, where suitability increases from 0 when there are no low-velocity areas to 1 when the entire habitat is low velocity.

V₉ – Gradient. Gradients ≥0.5% (5 m km⁻¹ [26 ft mi⁻¹]) are unsuitable for pike, but optimal suitability is not reached until the gradient is <0.1%.

For most HSI model variables, Central Valley field data were not available or were only available qualitatively (Table 4), requiring subjective evaluation of habitat suitability rather than rigorous quantitative application of the model. Variables with no information include the ratio of spawning habitat to summer habitat (V₁), percentage of summer habitat with vegetation (V₃), and percentage of pools or backwaters in summer (V₈).

Values for other HSI variables are so consistent among habitats that they offer no insight into relative suitability, but do indicate whether the Central Valley, in general, offers good conditions for northern pike colonization. These include TDS (V₄), pH (V₅), and average length of the frost-free season (V₆). Total dissolved solids is not included as

a variable in Table 4, but probably falls within the optimal range (0.08-0.8 ppt) in all areas except the Suisun Marsh, and, possibly, some areas of the San Joaquin River. If North American pike have the same salinity tolerance as those in Europe, all areas upstream of Carquinez Strait are habitable.

All areas except the San Joaquin River (with high summer values) have pH levels that are adequate year-round for pike (Table 4).

The relationship between the length of the frost-free season and pike gonadal development was inferred from a laboratory study of yellow perch and has not been tested in the field. Its speculative nature, and the fact that it is based on a species from a different family than pike, makes it of little utility for predicting the success of pike invasion of the Central Valley.

Values of the three remaining HSI variables indicate that pike would survive in many areas of the Central Valley, but also differ sufficiently among habitats to suggest where pike would do best. For pike that select preferred spawning habitat (<1 m [3.3 ft] deep), a decrease in water level during the incubation and larval stages (V_2) would be detrimental to reproductive success. In these areas, a decrease of 1 m (3.3 ft) during the critical ca. 50-day period between spawning and post-larval emigration would lead to total mortality. Therefore, some of the low-velocity, shallow, well-vegetated areas that might otherwise be considered to be good pike spawning habitat may be unsuitable, at least in some years, because of rapid and/or frequent water level fluctuations. These include Thermolito Afterbay, the Feather River from the Thermolito Afterbay outlet to the Sacramento River, the Sutter and Yolo bypasses, the American River, and the Cosumnes River (Table 4). Pike spawning in other areas or in deeper water would not be subject to this limitation. Also, the longevity of pike indicates that successful reproduction every year is not necessary for persistence. Adequate abundance could be maintained by intermittent successful year classes, in the same manner as for native white sturgeon (*Acipenser transmontanus*) (Kohlhorst et al. 1991) and Sacramento splittail (Moyle 2002).

Even though pike is a cool-water species, maximum water temperature (V_7) is adequate in most Central Valley habitats. Although adequate for pike survival, maximum temperature is too cool for good growth in the Thermolito Diversion Pool and in the

Sacramento River from Red Bluff Diversion Dam to Chico Landing. It is too warm for the best survival in lower Mill and Deer, Big Chico, and Butte creeks; the lower San Joaquin tributary rivers; and some places in the delta (Table 4).

Stream gradient (V_9) has only been described in qualitative terms in this report (Table 4). The highest gradient streams in the Central Valley – and the least suitable for pike based on this criterion – are the Sacramento River from Red Bluff Diversion Dam to Chico Landing and Big Chico Creek. This is somewhat deceptive, as many low gradient off-channel areas are available to pike in both these areas.

Based on application of these criteria to the Central Valley, it appears that many areas will offer adequate habitat for one or more northern pike life stages (Table 5). Several waters, including Thermolito Forebay, the Feather River downstream from the Thermolito Afterbay outlet at least to the mouth of the Yuba River, the lower Mokelumne River, and the delta will provide good habitat for some life stages; the best pike habitat appears to occur in Thermolito Forebay and the delta.

In addition to the use of this HSI model, Moyle and Marchetti (2006) have described subjective criteria for predicting invasion success in freshwater habitats in California. They conclude that the factors that best predict invasion success are (1) history of successful establishment outside its native range, (2) characters that promote success at multiple stages of the invasion process (e.g., high physiological tolerance), (3) invaded habitat that more or less matches the invader's native habitat, (4) high fish species richness, including other non-native fishes, and (5) propagule size exceeding 100 individuals. These criteria apply to the Central Valley as a whole and not to individual habitats. These authors also point out that it is much easier to look back on an invasion by a non-native species and see why it was successful than to predict the course of future invasions.

As concluded by evaluation of the pertinent variables in the HSI model, the above general criteria indicate that the northern pike would establish a population if it invaded the Central Valley. Pike (1) has a history of successful establishment when introduced outside its native range, (2) would tolerate the abiotic environment of most habitats it would encounter, (3) would find some habitat that reasonably matches its native habitat, (4) would find a species-rich community of native and non-native fishes, (5) would reach

the Central Valley in large enough numbers to allow establishment. On the latter point, pike could be introduced to the Central Valley in two ways: via the Middle Fork Feather River and Lake Oroville or by intentional transport from Lake Davis to other lake(s) in the Central Valley watershed. As Moyle and Marchetti (2006) point out, the need for adequate propagule size can be met in one introduction or through successive introductions, as might occur with repeated movement into Lake Oroville, limited reproduction there, and emigration downstream.

CONCLUSION

Northern pike can tolerate a wide variety of environmental conditions and are likely to successfully invade many waterways if they reach the Central Valley through downstream movement from Lake Davis or intentional illegal introduction. They have the potential to survive in many areas and become abundant in some habitats. In other areas their success may be reduced by suboptimal turbidity, water velocity, water level fluctuation, and extent and density of submerged vegetation. They would prey on nearly every native fish species, many of which are already in decline, and prey on or compete with many non-native fishes. Results of introductions of pike elsewhere, and of other predatory fish in California, suggest that pike could have a devastating effect on existing Central Valley fish communities. The overall ecosystem effect of the resultant change in species composition is impossible to predict, but given the current stressed state of the Central Valley and San Francisco Bay Estuary aquatic environments, any additional negative impacts should be avoided. Therefore, the only prudent management alternative is to use all means necessary to prevent northern pike from reaching the Central Valley.

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REFERENCES

- Adelman IR, Smith LL. 1977. Effect of oxygen on growth and food conversion efficiency of northern pike. *Progressive Fish-Culturist* 32:93-96.
- Allen KR. 1939. A note on the food of pike (*Esox lucius* L.) in Windmere. *Journal of Animal Ecology* 8:72-75.
- Anderson PG. 1993. Adaptation of a habitat suitability model for prioritizing habitat rehabilitation needs of northern pike (*Esox lucius*) [MS thesis]. Peterborough (Ontario, Canada): Trent University.
- Associated Press. 2003. Biologist goes after non-native pike. *Fairbanks Daily News-Miner*, October 17, 2003.
- Beyerle GB, Williams JE. 1968. Some observations of food selectivity by northern pike in aquaria. *Transactions of the American Fisheries Society* 97:28-31.
- Billard R. 1996. Reproduction of pike: gametogenesis, gamete biology and early development. In: Craig JF, editor. *Pike biology and exploitation*. New York: Chapman and Hall. p 13-43.
- Brown LR. 2000. Fish communities and their associations with environmental variables, lower San Joaquin River drainage, California. *Environmental Biology of Fishes* 57 (3): 251-269.
- Brown RL. 1987. Suisun Marsh Vegetation Survey. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, Technical Report 10.
- Bry C. 1996. Role of vegetation in the life cycle of pike. In: Craig JF, editor. *Pike biology and exploitation*. New York: Chapman and Hall. p 45-67
- CALFED Bay-Delta Program. 1999. Ecological management zone visions, revised draft. Ecosystem restoration program plan, volume 2.
- California Department of Fish and Game. 1991. Lower Mokelumne River fisheries management plan. November 1991.
- Central Valley Regional Water Quality Control Board (CVRWQCB). 1991. Water quality of the lower San Joaquin River: Lander Avenue to Vernalis, water year 1990.
- Carbine WF, Applegate VC. 1948. The movement and growth of marked northern pike (*Esox lucius*, L.) in Houghton Lake and the Muskegon River. *Papers of the Michigan Academy of Science, Arts, and Letters* 32:215-38.

- Carlander KD., Campbell JS, Muncy RJ. 1978. Inventory of percid and esocid habitat in North America. American Fisheries Society Special Publication 11:27-38.
- Casselman JM. 1978. Effects of environmental factors on growth, survival and exploitation of northern pike. American Fisheries Society Special Publication 11: 114-128.
- Casselman JM. 1983. Age and growth assessment of fish from their calcified structures – techniques and tools. In: Prince ED, Pulos LM, editors. Proceedings of the international workshop on age determination of oceanic pelagic fishes: tunas, billfishes, and sharks. NOAA Technical Report NMFS 8:1-17.
- Casselman JM. 1996. Age, growth and environmental requirements of pike. In: Craig JF, editor. Pike biology and exploitation. New York: Chapman and Hall. p 69-101.
- Casselman JM, Lewis CA. 1996. Habitat requirements of northern pike (*Esox lucius*). Canadian Journal of Fisheries and Aquatic Science 53(Suppl.1):161-174.
- Chapleau F, Findlay CS. 1997. Impact of piscivorous fish introductions on fish species richness of small lakes in Gatineau Park, Quebec. Ecoscience. 4(3):259-268.
- Chapman LJ, Mackay WC, Wilkinson CW. 1989. Feeding flexibility in northern pike (*Esox lucius*): fish versus invertebrate prey. Canadian Journal of Fisheries and Aquatic Science 46:666-669.
- Chapman CA, Mackay WC. 1984. Direct observations of habitat utilization by northern pike. Copeia 1984 (1):255-258.
- Craig JF, Babaluk JA. 1989. Relationship of condition of walleye (*Stizostedion vitreum*) and northern pike (*Esox lucius*) to water clarity with special reference to Dauphin Lake, Manitoba. Canadian Journal of Fisheries and Aquatic Science 46:1581-1586.
- Crossman EJ. 1978. Taxonomy and distribution of North American Esocids. American Fisheries Society Special Publication 11:13-26.
- Derksen AJ, Gillies DG. 1985. The seasonal utilization of the Saskeram Marshes by fish populations and its significance to the fisheries resources of the Saskatchewan River delta in Manitoba, with special reference to northern pike. Fisheries Branch Manuscript Report 85-10. Winnipeg (Manitoba, Canada): Manitoba Department of Natural Resources.
- Diana JS. 1983. Growth, maturation, and production of northern pike in three Michigan lakes. Transactions of the American Fisheries Society 112:38-46.

- Durand JP, Gas JM. 1976. Quelques aspects de la reproduction du brochet (*Esox lucius* L., 1758) dans la Seine au niveau de Montereau Croissance et comportement des alvins, dan diverses conditions experimentales. Memoire ISARA, Leon. 108 pp.
- Fabrizius E, Gustafson KJ. 1958. Some new observations on the spawning behaviour of the pike, *Esox lucius* L. Drottningholm (Sweden): Institute of Freshwater Research, Report No. 39:23-54.
- Fay V. 2002. Strategic response plans, nonindigenous northern pike populations. In: Fay V., primary author. Alaska aquatic nuisance species management plan. Juneau (AK): Alaska Department of Fish and Game. Appendix H.
- Forney JL. 1968. Production of young northern pike in a regulated marsh. New York Fish and Game Journal 15:143-54.
- Franklin DR, Smith LL Jr. 1963. Early life history of northern pike, *Esox lucius* L., with special reference to the factors influencing the numerical strength of year classes. Transactions of the American Fisheries Society 92:91-110.
- Friant Waters User Authority and Natural Resources Defense Council (FWUA and NRDC). 2000. San Joaquin River restoration plan. Technical workshop 1. November 14-15, 2000.
- Frost WE. 1954. The food of pike, *Esox lucius*, L., in Windmere. Journal of Animal Ecology 23:339-360.
- Gerlich GW. 2001. Spinney Mountain Reservoir fisheries management plan (draft). Colorado Division of Wildlife. 31p.
- Gravel Y, Dube J. 1980. Les conditions hydriques et le role de la vegetation dans une frayerie a grands brochets *Esox lucius* Linne. Eau du Quebec 13:229-230.
- Grimm MP, Backx, JJGM. 1990. The restoration of shallow eutrophic lakes, and the role of northern pike, aquatic vegetation, and nutrient concentration. Hydrobiologia 200/201:557-566.
- Grimm MP, Klinge M. 1996. Pike and some aspects of its dependence on vegetation. In: Craig JF, editor. Pike biology and exploitation. New York: Chapman and Hall. p 125-156.
- Harvey HH. 1980. Widespread and diverse changes in the biota of Northern American lakes and rivers coincident with acidification. In: Drablos D, Tolan A, editors. Proceedings of an International Conference, Sandefjord, Norway. p 93-98.

- Hassler TJ. 1970. Environmental influences on early development and year-class strength of northern pike in Lakes Oahe and Sharpe, South Dakota. Transactions of the American Fisheries Society 99:369-375.
- Hokanson KEF, McCormick JH, Jones BR. 1973. Temperature requirements for embryos and larvae of the northern pike, *Esox lucius* (Linnaeus). Transactions of the American Fisheries Society 102:89-100.
- Hunt BP, Carbine WF. 1950. Food of young pike, *Esox lucius*, L., and associated fishes in Peterson's ditches, Houghton Lake, Michigan. Transactions of the American Fisheries Society 80:67-83.
- Inskip PD. 1982. Habitat suitability index models: northern pike. U.S. Fish and Wildlife Service. FWS/OBS-82/10.17.
- Jenkins RE, Burkhead NM. 1994. Freshwater fishes of Virginia. Bethesda (MD): American Fisheries Society. 1079p.
- Johnson T, Muller K. 1978. Migration of juvenile pike, *Esox lucius* L., from a coastal stream to the northern part of the Bothnian Sea. Aquilo. Serie Zoologica 18:57-61.
- Jones and Stokes Associates, Inc. 1993. Sutter Bypass fisheries technical memorandum II: Potential entrapment of juvenile chinook salmon in the proposed gravel mining pond. Prepared for Teichert Aggregates, Sacramento (CA).
- Jones and Stokes Associates, Inc. and VTN Sacramento. 1974. Cosumnes River Basin resources study: final report.
- Kipling C. 1983. Changes in the population of pike (*Esox lucius*) in Windermere from 1944 to 1981. Journal of Animal Ecology 52:647-657.
- Knight NJ. 1985. Microhabitats and temperature requirements of hardhead (*Mylopharodon conocephalus*) and Sacramento squawfish (*Ptychocheilus grandis*), with notes for some other native California stream fishes (Dissertation). Davis (CA): University of California, Davis. 161p.
- Kohlhorst DW, Botsford LW, Brennan JS, Cailliet GM. 1991. Aspects of the structure and dynamics of an exploited central California population of white sturgeon (*Acipenser transmontanus*). In: Willoit, P, editor. Acipenser, Actes du Premier Colloque International sur l'esturgeon. Bordeaux, France. p 277-293.
- Lagler KF. 1956. Freshwater fishery biology, 2nd Edition. Dubuque (IA): Wm. C. Brown Co.
- Lawler GH. 1965. The food of pike *Esox lucius*, in Heming Lake Manitoba. Journal of the Fisheries Research Board of Canada 22:1357-1377.

- Leland HV, Fend SV. 1998. Benthic invertebrate distributions in the San Joaquin River California, in relation to physical and chemical factors. *Canadian Journal of Fisheries and Aquatic Science* 55:1051-1067.
- Lillelund Von K. 1966. Versuche zur Erbrutung der Eier vom Hecht, *Esox lucius* L., in Abhangigkiet von Temperatur und Licht. *Archiv Fischereiwiss* 17:95-113.
- Lux FE, Smith LL. 1960. Some factors influencing seasonal changes in angler catches in a Minnesota lake. *Transactions of the American Fisheries Society* 89:67-79.
- Mann RHK. 1982. The annual food consumption and prey preferences of pike (*Esox lucius*) in the River Frome, Dorset. *Journal of Animal Ecology* 51:81-95.
- Margenau TL, Rasmussen PW, Kampa JM. 1998. Factors affecting growth of northern pike in small northern Wisconsin lakes. *North American Journal of Fisheries Management* 18:625-639.
- Masse G, Fortin R, Dumont P, Ferraris J. 1988. Etude et aménagement de la frayere multispecifique de la riviere aux Pins et dynamique de la population de Grand Brochet, *Esox lucius* L., du fleuve Saint-Laurent, Boucherville, Quebec. Quebec, Ministère du Loisir, de la Chasse et de la Pêche, Service de l'aménagement et de l'exploitation de la faune, Rapport Technique No. 06-40. 224p.
- Masse G, Dumont P, Ferraris J, Fortin R. 1991. Influence des regimes hydrologique et thermique de la riviere aux Pins (Quebec) sur les migrations de fraie du Grand Brochet et sur l'avaliason des jeunes brochets de l'annee. *Aquatic Living Resources* 4:275-287.
- McCarraher DB. 1962. Northern pike, *Esox lucius*, in alkaline lakes of Nebraska. *Transactions of the American Fisheries Society* 91:326-329.
- Moyle PB. 1976. *Inland fishes of California*. Berkeley (CA): University of California Press.
- Moyle PB. 2002. *Inland fishes of California*, revised and expanded. Berkeley (CA): University of California Press. 502p.
- Moyle PB, Baltz DM. 1985. Microhabitat use by an assemblage of California stream fishes: developing criteria for instream flow recommendations. *Transactions of the American Fisheries Society* 114:695-704.
- Moyle PB, Cech JJ Jr. 1982. *Fishes: An introduction to ichthyology*. Englewood Cliffs (NJ): Prentice-Hall.

- Moyle PB, Herbold B, Stevens DE, Miller LW. 1992. Life history and status of the delta smelt in the Sacramento-San Joaquin Estuary, California. *Transactions of the American Fisheries Society* 121:67-77.
- Moyle PB, Nichols RD. 1973. Ecology of some native and introduced fishes of the Sierra-Nevada foothills, central California. *American Midland Naturalist* 92:72-83.
- Moyle PB, Yoshiyama RM, Williams JE, Wikramanayake ED. 1995. Fish species of concern in California, second edition. Rancho Cordova (CA): California Department of Fish and Game.
- Muller K. 1986. Seasonal anadromous migration of the pike (*Esox lucius* L.) in coastal areas of the northern Bothnian Sea. *Archiv fuer Hydrobiologie* 107(3):315-330.
- Orabutt DE. 2006. Northern pike in selected Colorado trout reservoirs [MS thesis]. Ft. Collins (CO): Colorado State University. 63p.
- Petit GD. 1973. Effects of dissolved oxygen on survival and behavior of selected fishes of western Lake Erie. *Bulletin of the Ohio Biological Survey, New Series* 4:1-76.
- Pierce RB. 1997. Ecological and life history associations of northern pike with aquatic vegetation – a literature review. Unpublished.
- Raat AJP. 1988. Synopsis of biological data on the northern pike *Esox lucius* Linnaeus, 1758. Rome (Italy): FAO Fisheries Synopsis, no. 30 (Revision 2). 178 pp.
- Savino JF, Stein RA. 1989. Behavior of fish predators and their prey: habitat choice between open water and dense vegetation. *Environmental Biology of Fishes* 24:287-293.
- Schlumpberger V. 1966. Determination of salt tolerance of pike (*Esox lucius*) by means of Na²². *Ref. Zh. Biol.* 11:118K (in Russian).
- Schroeter RE, Moyle PB. 2001. Trends in fish populations of Suisun Marsh, January 2000-December 2000. Sacramento (CA): Annual Report for Contract SAP 4600000986, California Department of Water Resources, Central Division.
- Siefert RE, Spoor WA, Syrett RF. Effects of reduced oxygen concentrations on northern pike (*Esox lucius*) embryos and larvae. *Journal of the Fisheries Research Board of Canada* 30:849-852.
- Sommer T, Harrell B, Nobriga M, Brown R, Moyle P, Kimmerer W, Schemel L. 2001. California's Yolo Bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries* 26 (8):6-16.

- Sukhanova GI. 1979. The spawning and fecundity of the pike *Esox lucius* in Vilyuy reservoir. *Journal of Ichthyology* 19:74-79.
- Swift DR. 1965. Effect of temperature on mortality and rate of development of the eggs of the pike (*Esox lucius* L.) and the perch (*Perca fluviatilis* L.). *Nature* 206:528.
- Toner ED, Lawler GH. 1969. Synopsis of biological data on the pike, *Esox lucius* (Linnaeus 1758). Rome (Italy): FAO Fish Synopsis 30, Revision 1. 38 p.
- U.S. Army Corps of Engineers (USACE). 1972. Environmental impact statement, New Melones Lake, Stanislaus, CA. Sacramento (CA).
- USACE, Sacramento District. 1991. American River watershed investigation, California feasibility report, parts I and II. Sacramento (CA).
- U.S. Fish and Wildlife Service (USFWS), Sacramento office. 1999. Draft programmatic environmental assessment, anadromous fish restoration actions in lower Deer Creek, Tehama County, CA. Prepared for Sacramento-San Joaquin Estuary Fishery Resource Office, USFWS, Stockton, CA.
- USFWS, Sacramento office. 2000. Draft programmatic environmental assessment, anadromous fish restoration actions in lower Mill Creek, Tehama County, CA. Prepared for Sacramento-San Joaquin Estuary Fishery Resource Office, USFWS, Stockton, CA.
- U.S. Geological Survey. 1978. Observations of water quality in the mixed reach below the confluence of the Sacramento and Feather rivers, California. August and November 1975. *Water Resources Investigation* 77-91.
- Wang JCS. 1986. Fishes of the Sacramento-San Joaquin estuary and adjacent waters, California: A guide to the early life histories. Interagency Ecological Study Program for the Sacramento- San Joaquin Estuary, Technical Report 9.
- Weithman AS, Anderson RO. 1977. Survival, growth, and prey of esocidae in experimental systems. *Transactions of the American Fisheries Society* 106:424-430.
- Weitkamp DE. 2003. Potential northern pike control to enhance cutthroat trout survival, Coeur d'Alene Lake. Spokane River Hydroelectric Project, FERC Project No. 2545, Avista Corporation.
- Woodward-Clyde Consultants. 1986. Environmental investigation report for the Butte Basin overflow area. Prepared for the Reclamation Board, Sacramento, CA.

Table 1. Summary of Environmental Requirements of Northern Pike

Life Stage	Lethal low temp.	Lethal high temp.	Optimal temp.	DO (mg/l)	pH	Salinity (ppt)	TDS (ppm)	Veg. density	Prey
Embryo	5°C (41°F) ^a	28°C (82°F) ^{d,e}	7-18°C (44-64°F) ^b	>7 ^j	>5 ^l	<7 ⁿ	80-800 ^m	80% ^m	zooplankton ^r
Larval	<3°C (<38°F) ^b	26°C (78°F) ^b	22-23°C (72-73°F) ^c	>5 ^j	>5 ^l	<18 ^o	"	80% ^m	insects, small fish ^s
Juvenile	unknown	28°C (>82°F) ^f	19°C (66°F) ³	>1 ^k	5-9 ^l	<18 ^o	"	20-50% ^{16p}	fish, abundant items ^t
Adult	ca. 0°C (32°F) ^c	29-30°C (84-86°F) ^g	19°C (<66°F) ^c	>1.5 ^g	5-9 ^l	<18 ^o	"	30% ^{17q}	opportunistic ^u
Spawning	n/a	n/a	4-18°C (39-65°F) ^{a,h,i}	n/a	5-9 ^m	<7 ⁿ	"	80% ^c	n/a

^a Hassler 1970^b Hokanson et al. 1973^c Casselman and Lewis 1996^d Swift 1965^e Lillelund 1966^f Weithman and Andersen 1977^g Casselman 1978^h Sukhanova 1979ⁱ Fabricius and Gustafson 1958^j Siefert et al. 1973^k Petit 1973^l McCarraher 1962^m Inskip 1982ⁿ Svardson cited in Toner and Lawler 1969^o Jenkins and Burkhead 1994^p Anderson 1993^q Grimm and Backz 1990^r Hunt and Carbine 1951^s Savino and Stein 1989^t Bry 1996^u Mann 1982

Table 2. Reported northern pike growth throughout its range.

Age (years)	Fork Length (cm)	
	Mean	Range
1	18	9 – 33
2	33	15 – 51
3	43	23 – 64
4	48	28 – 74
5	56	33 – 81
6	61	38 – 86
7	64	43 – 89
8	69	43 – 94
9	71	48 – 97
10	76	56 – 109
11	71	43 – 97
12	69	51 - 97

Table 3. Native fishes of the Central Valley ranked by expected vulnerability to northern pike predation.

Species	Vulnerable live stages
Splittail	All
Rainbow trout/steelhead	Fry, juvenile
Chinook Salmon	Fry, juvenile
Sacramento sucker	Fry, juvenile
Sacramento pikeminnow	Fry, juvenile
Delta smelt	All
Longfin smelt	All
Hardhead	Fry, juvenile
Sacramento blackfish	Fry, juvenile
Hitch	Fry, juvenile
Speckled dace	All
California roach	All
Tule perch	All
Pacific and brook lampreys	Ammocoetes

Table 4. Environmental characteristics important to northern pike in California waters (Figure 5) that are subject to invasion by dispersal from Lake Davis.

Water Body	Vegetation	Water Velocity	Gradient	Annual Temp. Range (°C)	DO Mg/l	pH	Water Level Variation	Comments
Feather R. Middle Fork Sierra Valley	Present	Slow	Low	2-24	8.8- 13.1	7.4- 8.4		Multiple age classes of northern pike present before chemical treatment
Feather R. Middle Fork Sloat-Lake Oroville	Little	Fast ^a	High ^a	2-24 ^b	8.8- 13.1 ^b	7.4- 8.4 ^b		Likely only a corridor for pike to move to Lake Oroville
Lake Oroville	None ^b	n/a	n/a	7-24 ^b	7.8- 12.0 ^b	6.8- 7.4 ^b	High	
Thermolito Diversion Pool	Present ^c	n/a	n/a	Max. = 14			Little ^b	Very limited shallow-water habitat
Thermolito Forebay	Abundant ^c	n/a	n/a	10-17 ^b	9.1- 12.1 ^b	5.9- 8.1 ^b		Much shallow water
Thermolito Afterbay	Abundant ^c	n/a	n/a	10-17 ^b	8.9- 13.1 ^b	6.0- 8.6 ^b	Frequent ^b	Shallow, temp. reaches 29°C in bays
Oroville Wildlife Area Ponds	Present ^c						Frequent ^c	Summer water temp. may be too high for pike
Feather R., Lake Oroville- Sacramento R.	Present ^d	Fast – slow ^d	Moderate ^d	10-24 ^d			Frequent	Numerous bars, islands, and backwaters with slow-moving water and aquatic vegetation

Water Body	Vegetation	Water Velocity	Gradient	Annual Temp. Range (°C)	DO Mg/l	pH	Water Level Variation	Comments
Yuba R.	Scarce ^e	Moderate - fast ^e	Low ^e	8-18 ^f			Frequent	Shallow, high-water-velocity areas may inhibit pike movements; some areas of aquatic and marshy vegetation
Sacramento R. Red Bluff Diversion Dam-Chico Ldg.	Present ^e	Moderate ^e	Moderate	6-14 ^g	10.0-14.9 ^g		Frequent	Suitable spawning sites scarce because of fluctuating water levels and velocities in areas of aquatic and flooded terrestrial vegetation
Mill Creek			Low ^h	2-29 ^g			Frequent	Shallow in lower section, maybe some flooded terrestrial vegetation at high flows; high silt load; diversion dams in lower reach
Deer Creek	Scarce ⁱ		Moderate	0-27 ^g			Frequent	Diversion dams in lower reach

Water Body	Vegetation	Water Velocity	Gradient	Annual Temp. Range (°C)	DO Mg/l	pH	Water Level Variation	Comments
Sacramento R. Chico Ldg.-Verona	Present in Butte and Colusa basins ^j	Moderate-high	Low - moderate	9-22 ^k			Frequent	Butte and Colusa basins might provide spawning habitat some years, limited by water velocity, water level fluctuations, and high turbidity
Big Chico Creek	Scarce	Moderate-high	High	5-28 ^g			Frequent	Some pools in Bidwell Park
Butte Creek	Abundant some places ^j	Low-high ^l	Low ^l	2-26 ^g	9.0-12.7 ^l	7.1-7.9 ^l	Frequent	Numerous sloughs with vegetation, season and permanent wetlands
Sutter Bypass	Abundant ^m	Low-high ⁿ	Low			6.9-8.5 ^l	Frequent and rapid ^m	High turbidity/silt load and high water velocity when flooded
Yolo Bypass	Abundant ^o	Low-high	Low – mostly tidal				Frequent and rapid ^o	High turbidity/silt load and high water velocity when flooded

Water Body	Vegetation	Water Velocity	Gradient	Annual Temp. Range (°C)	DO Mg/l	pH	Water Level Variation	Comments
Sacramento R., Verona-Courtland	Scarce ^c	Moderate-high ^c	Low				Frequent	Little spawning habitat and few low velocity areas except behind wing dams north of Sacramento; highly channelized
American River	Present in ponds and backwaters ^p	Moderate-high ^p	Low-moderate	4-22 ^g			Frequent and rapid ^p	Much of river below Nimbus Dam probably not suitable
Cosumnes River	Abundant ^q	Low-high	Low, mostly tidal	10-26 ^r			Frequent ^r	Large flood plain with abundant terrestrial vegetation; high turbidity/silt load when flooded
Mokelumne River	Abundant ^{s,t}	Low-high	Low-moderate ^u	8-23 ^v				Lower river above the delta has abundant aquatic vegetation, but often high water velocity during late winter-spring

Water Body	Vegetation	Water Velocity	Gradient	Annual Temp. Range (°C)	DO Mg/l	pH	Water Level Variation	Comments
San Joaquin R., Friant Dam-Merced R.		Dry-high ^w	Low	4-27 ^g	4.4-8.6 ^x	7.1-9.9 ^w	Substantial, upper portion dry most of year	Wetland sloughs may provide spawning habitat, receives substantial agricultural drainage
San Joaquin R., Merced R.-Vernalis	Limited ^c	Moderate	Low			6.6-9.3 ^y	Substantial	Highly channelized
Merced River	Scarce ^{z,aa}	Moderate	Low	7-27 ^g	7.5-7.9 ^x	7.5-7.9 ^s	Moderate	Dredger ponds with vegetation could provide spawning habitat
Tuolumne River	Present ^{aa}	Low-moderate	Low	9-29 ^g	6.8-9.5 ^s	7.4-8.1 ^s	Moderate	Dredger ponds with vegetation could provide spawning habitat
Stanislaus River	Present ^{z,bb}	Low-moderate	Low	8-26 ^{cc}	8.3-9.6 ^s	7.6-7.7 ^s	Moderate	Dredger ponds with vegetation could provide spawning habitat
Calaveras River, below Bellota Dam		Low-high	Low				High	High winter-spring flows and low, stagnant summer conditions

Water Body	Vegetation	Water Velocity	Gradient	Annual Temp. Range (°C)	DO Mg/l	pH	Water Level Variation	Comments
Sacramento-San Joaquin Delta	Abundant – submerged aquatic, tules, riparian ^e	Low-moderate tidal current ^e	Low	6-28 ^{dd}	2.0-14.9 ^{dd}		Tidal	TDS>0.5 ppt in western and southern delta; extensive shallow flooded islands and tidal marshes
Suisun Marsh	Mostly emergent ^{ee}	Low-moderate tidal current ^{ff}	Low	10-23	4.4-10.3	7.0	Tidal	TDS from 0.9 to 6.8 ppt; turbidity is generally high

^a J. Wilcox, pers. comm.

^b Initial Information Package, Jan. 2001

^c E. See, CDWR, pers. comm.

^d B. Cavallo, CDWR, pers. comm.

^e CALFED 1999

^f Jones and Stokes Associates 1998, unpubl.

^g <http://cdec.water.ca.gov>

^h USFWS 2000

ⁱ USFWS 1999

^j Woodward-Clyde Consultants 1986

^k USGS 1978

^l <http://www.buttetecreekwatershed.org/ecr/new>

^m W. Shaul, pers. comm.

data

ⁿ Jones and Stokes Associates 1993

^o Sommer et al. 2001

^p USACE 1991

^q Jones and Stokes Associates 1974

^r P. Crain pers. comm.

^s M. Workman, pers. comm.

^t J. Merz, pers. comm.

^u CDFG 1991

^v EBMUD 1996

^w FWUA and NRDC 2000

^x Leland and Fend 1998

^y CVRWQCB 1991

^z Brown 2000

^{aa} K. Kundargi, pers. comm.

^{bb} USACE, EIR 1972

^{cc} <http://water.wr.usgs.gov/data>

^{dd} L. Grimaldo, CDWR, unpubl.

^{ee} Brown 1987

^{ff} Schroeter and Moyle 2001

Table 5. Predicted suitability of Central Valley waterways for northern pike. Symbols indicate that the waterway would likely be poor (+), adequate (++), or good (+++) habitat for each life stage.

AREA	Spawning	Larval	Juvenile	Adult	Comments
Feather R. Middle Fork, Sierra Valley	+++	+++	+++	+++	Low gradient section in Sierra Valley known to support pike
Feather R. Middle Fork, Sloat-Lake Oroville	+	+	+	+	High gradient, little vegetation
Lake Oroville	+	+	+	++	
Thermalito Diversion Pool	+	+	+	+	Temps. below optimal for growth
Thermalito Forebay	+++	+++	+++	+++	Cool, shallow water with aquatic vegetation
Thermalito Afterbay	++	++	+++	+++	Shallow water with aquatic vegetation; fluctuating water level
Oroville Wildlife Area Ponds	++	++	++	++	Flooding would have to occur for spawning
Feather R., Oroville- Sacramento R.	++	++	++	+++	Backwater areas with aquatic vegetation
Yuba River	++	++	++	++	Some areas of slow velocity and patchy aquatic vegetation
Sacramento R., RBDD- Chico Landing	++	++	++	++	Some aquatic vegetation and backwater areas
Mill Creek	+	+	+	++	High turbidity, no aquatic vegetation information
Deer Creek	+	+	+	+	Little relevant information
Sacramento R., Chico Ldg.-Verona	+	+	+	+	Highly channelized
Big Chico Creek	+	+	+	++	Some spawning habitat; high summer temperatures
Butte Creek	++	++	++	++	Butte Basin area for spawning
Sutter Bypass	++	++	+	+	Aquatic vegetation for spawning, but may be too turbid and water level in low velocity areas too unstable

AREA	Spawning	Larval	Juvenile	Adult	Comments
					Aquatic vegetation for spawning, but may be too turbid and water level in low velocity areas
Yolo Bypass	++	++	+	+	too unstable
Sacramento R., Verona-Courtland	+	+	+	+	Highly channelized
American River	++	++	++	++	Some areas of patchy aquatic vegetation
					Large floodplain with abundant aquatic
Cosumnes River	++	++	++	++	vegetation; fluctuating water level
					Variable water velocity and high density of
Mokelumne River	++	++	+++	+++	aquatic vegetation
San Joaquin R., Friant Dam-Merced R.	++	++	++	++	Some spawning areas, but summer temperatures in lethal range
San Joaquin R., Merced R.-Vernalis	+	+	+	+	Highly channelized
					Dredger ponds and slow sections of river with
Merced River	++	++	++	++	aquatic veg.
					Dredger ponds and slow sections of river with
Tuolumne River	++	++	++	++	aquatic veg.
Stanislaus River	++	++	++	++	Dredger ponds would provide spawning habitat.
Calaveras River below Bellota	+	+	+	++	Not enough information available.
Sacramento-San Joaquin Delta	+++	+++	+++	+++	Slow water velocity and high density of aquatic vegetation.
					High turbidity and little aquatic vegetation
Suisun Marsh	+	+	+	+	besides tules.

FIGURE CAPTIONS

Figure 1. Native and introduced range of northern pike in North America. Adapted from Crossman (1978).

Figure 2. Potential northern pike habitat in California's Central Valley, including locations of present or previous occurrence.

Figure 1

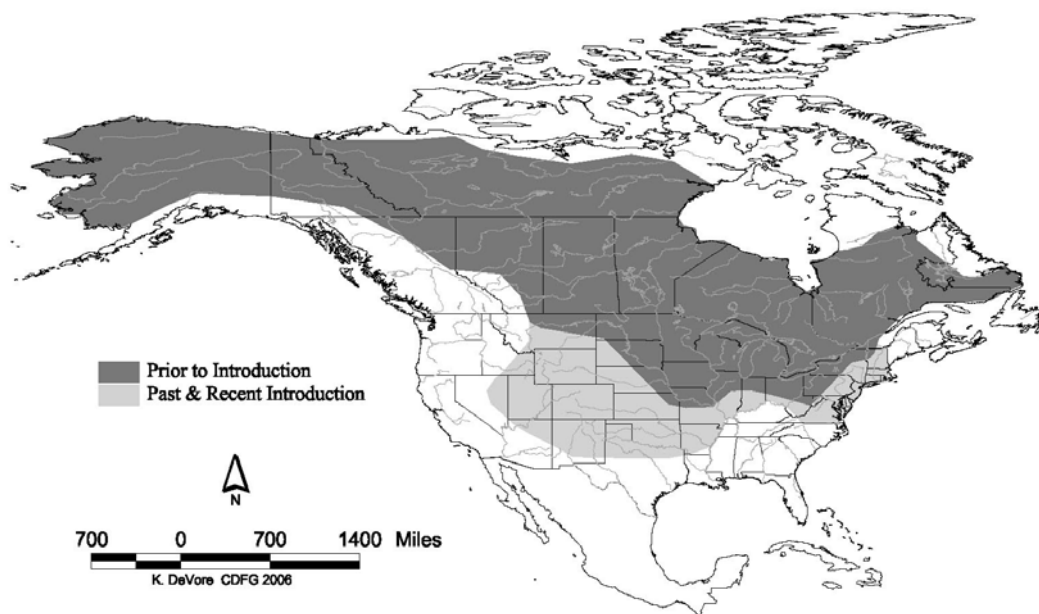


Figure 2

